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Pin Power Reconstruction in COSIMA

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September 1990

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PIN POWER RECONSTRUCTION IN COSIMA

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Abstract. The BWR core simulator code, COSIMA, has been extended with 3 new subroutines, PINPOW, COEFF1, and COEFF2, making it possible to extract single fuel pin powers from the nodal reactor calculations. The methods used are described.

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CONTENTS

1. INTRODUCTION

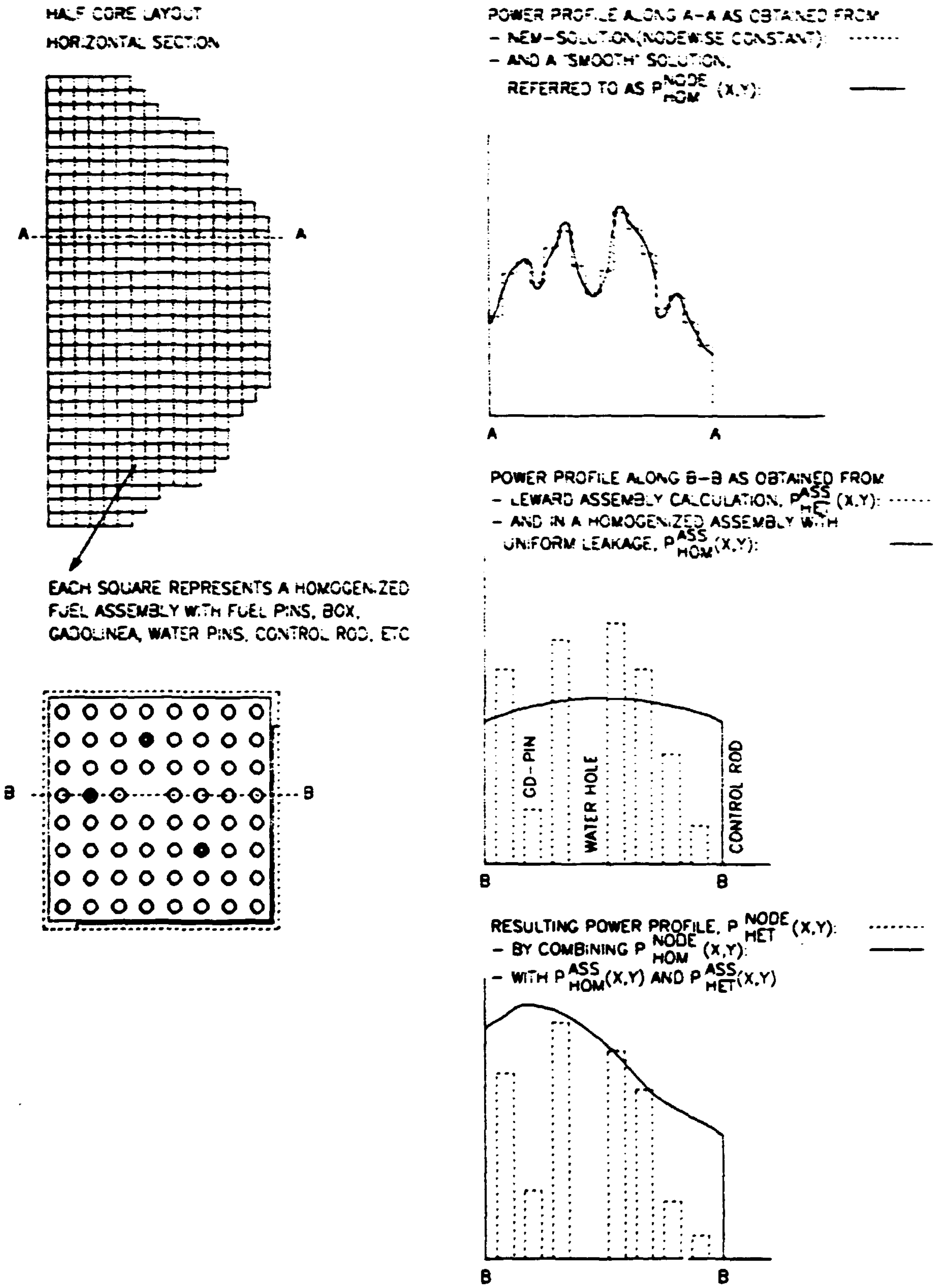
The Nodal Expansion Method (NEM), (1), (2), provides a fast and accurate method of calculating flux and power distributions in a reactor core. The core is divided into large homogenized nodes (typically a node represents a ~ 15 cm section of a fuel assembly). A large core may typically be represented in half-core geometry by some 10,000 nodes. The NEM solution gives the node averages of the flux, power etc., but no direct information about the detailed structures inside the nodes.

From the initial assembly calculations, which provide tables of cross sections etc. for the NEM calculations, the detailed pin power distributions are of course known, (but with certain standardized assumptions made about the surroundings of the assembly) and a first estimate of the pin power distribution in the node would simply be such an assembly distribution normalized to the average node power.

The NEM solution, however, contains much more information than just the average flux. The average fluxes at the node edges (surfaces), and the average in- and outgoing currents through the node edges (surfaces) are known as well, and it is therefore possible to construct, to some degree of accuracy, the continuous over-all structure of the flux, as it would be, if the cross sections etc. were node-wise constant.

This "homogeneous" flux (and power) is then used for superposition with the heterogeneous assembly pin power distributions to obtain the "true" pin power distributions of the nodes. The procedure is sketched in Fig. 1.

FIG. 1


HALF CORE LAYOUT
HORIZONTAL SECTION
A
A
EACH SQUARE REPRESENTS A HOMOGENIZED FUEL ASSEMBLY WITH FUEL PINS, BOX, GADOLINEA, WATER PINS, CONTROL ROD, ETC
B
B
POWER PROFILE ALONG A–A AS OBTAINED FROM
– AND A "SMOOTH" SOLUTION,
A
A
POWER PROFILE ALONG B–B AS OBTAINED FROM
– AND IN A HOMOGENIZED ASSEMBLY WITH UNIFORM LEAKAGE, P ASS HOM (X,Y):
CD–PIN
WATER HOLE
CONTROL ROD
B
B
RESULTING POWER PROFILE, P NODE HET (X,Y):
– BY COMBINING P NODE HOM (X,Y):
– WITH P ASS HOM (X,Y) AND P ASS HET (X,Y)
B
B

2. METHODS

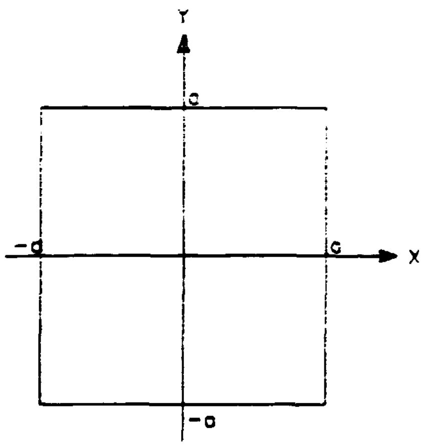
The methods outlined below are closely following those of (3), although minor modifications have been made.

Considering only the x-y plane, we expand the homogeneous flux in each group, g, inside a square node by

$$\phi^g(x,y) = \sum_{ij} a_{ij}^g x^i y^j$$

and leave for the rest of the treatment the group index g.

We choose the centre of the node as the origin of the x-y coordinate system and denote the side length of the square node by 2a.



For the average node flux we obtain:

$$\bar{\Phi} = \frac{1}{4a^2}\int_{-a}^{a}dx\int_{-a}^{a}dy\sum_{ij} a_{ij}x^i y^j$$

$$= \frac{1}{4a^2}\sum_{ij} a_{ij}\frac{1}{i+1}\,\frac{1}{j+1}\,(a^{i+1}-(-a)^{i+1}) * (a^{j+1}-(-a)^{j+1}) \tag{1}$$

For the average fluxes along the four edges we get:

$$\bar{\Phi}(y=\pm a) = \frac{1}{2a}\int_{-a}^{a}dx\sum_{ij} a_{ij}(\pm a)^j x^i$$

$$= \frac{1}{2a}\sum_{ij} a_{ij}(\pm a)^j\frac{1}{i+1}\,(a^{i+1}-(-a)^{i+1}) \tag{2}$$

$$\bar{\Phi}(x=\pm a) = \frac{1}{2a}\sum_{ij} a_{ij}(\pm a)^i\frac{1}{j+1}\,(a^{j+1}-(-a)^{j+1})$$

From the NEM solution we know for each node:

- The average node flux,
- The average in- and out-currents through each of the four edges, $J^+(x=\pm a)$, $J^-(x=\pm a)$, $J^+(y=\pm a)$, $J^-(y=\pm a)$.

This suggests that the full 9 terms expansion

$$\Phi(x,y) = \sum_{i=0,j=0}^{2,2} a_{ij}\, x^i\, y^j$$

can be constructed. It turns out, however, that the system of equations is 4-fold singular, such that only 5 coefficients a_{ij}, having either i=0 <u>or</u> j=0, can be determined.

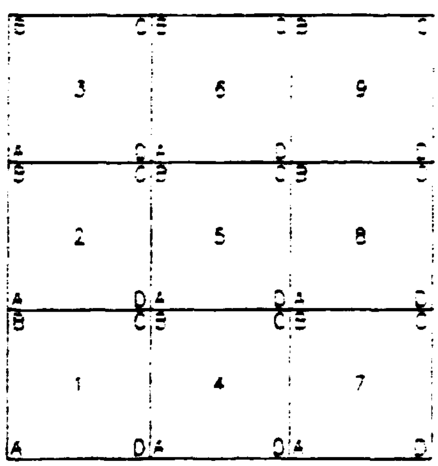
To find the average edge fluxes, we use

$$\Phi=2*(J^{+}+J^{-}) \tag{3}$$

and the resulting system of equations is obtained by combining (1), (2), and (3):

$$\begin{pmatrix} 1 & 0 & \frac{a^2}{3} & 0 & \frac{a^2}{3} \\ 1 & -a & a^2 & 0 & \frac{a^2}{3} \\ 1 & +a & a^2 & 0 & \frac{a^2}{3} \\ 1 & 0 & \frac{a^2}{3} & -a & a^2 \\ 1 & 0 & \frac{a^2}{3} & +a & a^2 \end{pmatrix} * \begin{pmatrix} a_{00} \\ a_{01} \\ a_{02} \\ a_{10} \\ a_{20} \end{pmatrix} = \begin{pmatrix} \bar{\Phi} \\ \bar{\Phi}(y=-a) \\ \bar{\Phi}(y=+a) \\ \bar{\Phi}(y=-a) \\ \bar{\Phi}(y=+a) \end{pmatrix} \tag{4}$$

Consider now a node (5) surrounded by its 8 neighbouring nodes:



In order to find the flux in the corner point A of the node no.5, we solve the above system of equations successively for the nodes: 1, 2, 4, 5 and thus gets 4 different values for the point:

$$\Phi_1(C)\,,\ \Phi_2(D)\,,\ \Phi_4(B)\,,\ and\ \Phi_5(A)$$

We now make a new single value for this corner flux as the simple average of the four mentioned:

$$F_A=(\Phi_1(C)+\Phi_2(D)+\Phi_4(B)+\Phi_5(A))/4$$

The same procedure is applied to the 3 other corners of node 5 and a new flux expansion can now be constructed, satisfying, in addition to the average node flux and the average edge fluxes as in (4), also the four new corner flux values.

Thus the full expansion, i,j = 0,1,2 can now be made, the system of equations being:

$$\begin{pmatrix} 1 & 0 & \frac{a^2}{3} & 0 & 0 & 0 & \frac{a^2}{3} & 0 & \frac{a^4}{9} \\ 1 & -a & a^2 & 0 & 0 & 0 & \frac{a^2}{3} & -\frac{a^3}{3} & \frac{a^4}{3} \\ 1 & a & a^2 & 0 & 0 & 0 & \frac{a^2}{3} & \frac{a^3}{3} & \frac{a^4}{3} \\ 1 & 0 & \frac{a^2}{3} & -a & 0 & -\frac{a^3}{3} & a^2 & 0 & \frac{a^4}{3} \\ 1 & 0 & \frac{a^2}{3} & a & 0 & \frac{a^3}{3} & a^2 & 0 & \frac{a^4}{3} \\ 1 & +a & a^2 & -a & a^2 & -a^3 & a^2 & -a^3 & a^4 \\ 1 & a & a^2 & -a & -a^2 & -a^3 & a^2 & a^3 & a^4 \\ 1 & a & a^2 & a & a^2 & a^3 & a^2 & a^3 & a^4 \\ 1 & -a & a^2 & a & -a^2 & a^3 & a^2 & -a^3 & a^4 \end{pmatrix} * \begin{pmatrix} a_{00} \\ a_{01} \\ a_{02} \\ a_{10} \\ a_{11} \\ a_{12} \\ a_{20} \\ a_{21} \\ a_{22} \end{pmatrix} = \begin{pmatrix} \bar{\Phi} \\ \bar{\Phi}(y=-a) \\ \bar{\Phi}(y=+a) \\ \bar{\Phi}(y=-a) \\ \bar{\Phi}(y=+a) \\ F_A \\ F_B \\ F_C \\ F_D \end{pmatrix} \qquad (6)$$

The homogeneous power distribution in the node is obtained by multiplying the flux expansions for each energy group by the homogenized fission cross sections:

$$P_{HOM}^{NODE}(x,y) = \sum_{g} \Sigma_{fiss}^{g} * \sum_{ij} a_{ij}^{g} x^{i} y^{j} \tag{7}$$

From the assembly calculations, which produced the cross section tables etc. to the over-all NEM calculation, we have the detailed pin power distributions

$$P_{HET}^{ASS}(x,y),$$

as calculated under certain standardized boundary conditions for the assembly, e.g. totally reflective boundaries, or as we use in LEWARD (4), boundaries that reflect so many neutrons as to make k_{eff} for the assembly = 1.0.

If totally reflective boundaries were used, the flux- (and power-) distribution one would obtain treating the assembly as a homogenized square region, would be constant over the region

$$P_{HOM}^{ASS}(x,y) = 1.0.$$

In the more general case, where the boundaries are not totally reflective we do not get a spatially constant flux (or power) distribution, but some (slowly) varying distribution,

$$P_{HOM}^{ASS}(x,y)$$

Thus, if the homogeneus power distribution in the assembly is

$$P_{HOM}^{ASS}(x,y)$$

then the heterogeneous power distribution is

$$P_{HET}^{ASS}(x,y)$$

As we have found the true homogeneous power distribution in the node to be (from (7))

$$P_{HOM}^{NODE}(x,y)$$

a superposition principle leads to

$$P_{HET}^{NODE}(x,y) = P_{HET}^{ASS}(x,y) * \frac{P_{HOM}^{NODE}(x,y)}{P_{HOM}^{ASS}(x,y)} \tag{8}$$

Tabulating

$$P_{HET}^{ASS^*}(x,y) = \frac{P_{HET}^{ASS}(x,y)}{P_{HOM}^{ASS}(x,y)}$$

in stead of

$$P_{HET}^{ASS}(x,y) \quad \underline{and} \quad P_{HOM}^{ASS}(x,y)$$

saves storage and gives the final pin power formula:

$$P_{HET}^{NODE}(x,y) = P_{HET}^{ASS^*}(x,y) * P_{HOM}^{NODE}(x,y) \qquad (9)$$

3. IMPLEMENTATION OF THE PIN POWER RECONSTRUCTION CAPABILITY IN COSIMA

Three new subroutines have been written and incorporated in COSIMA (5):

- COEFF1 which sets up and solves the system of equations (4) in section 2.
- COEFF2 which sets up and solves the system of equation (6) in section 2.
- PINPOW which performs the trivial (but complicated) operations necessary to define the positions and orientations (control rod corners etc.) of the assemblies, for which the pin powers are to be

calculated. It also administers the calls of COEFF1 and COEFF2.

In the input data for the new time step the word PINPOWER causes reading of two more cards, which must comply with the following example:

```
NLEVEL= 8 LEVELS:  4  5  10  11  16  17  22  23
NASSEMBLY= 5 ASSEMBLIES: 16  17  50  230  258
```

which means that pin power calculations and print outs will be made for the assemblies (or channels) 16, 17, 50, 230, and 258 at the axial node levels 4, 5, 10, 11, 16, 17, 22, and 23.

The first page of the corresponding output is shown on the next page.

OUTPUT

```
PIN POWER RECONSTRUCTION:

CHANNEL NO.   16 AX. LEVEL NO.    4

CONTROL ROD POSITION IS:  NW

RESULTING POWER DISTRIBUTION:
(NORMALIZED SUCH THAT AVERAGE FOR ALL NODES = 1.0)

   1.231   1.250   1.198   1.240   1.241   1.271   1.255
   1.252   1.164   1.233   1.339   1.334   1.227   1.192
   1.202   1.235   1.113   1.214   1.253   1.097   1.255
   1.247   1.344   1.216   0.911   1.323   1.458   1.343
   1.248   1.341   1.259   1.326   0.755   1.553   1.336
   1.280   1.236   1.105   1.466   1.559   1.061   1.416
   1.264   1.203   1.267   1.355   1.345   1.422   1.354

RELATIVE NODE POWER:    1.261

RESULTING POWER DISTRIBUTION:
(NORMALIZED SUCH THAT AVERAGE FOR THIS NODE = 1.0)

   0.976   0.991   0.950   0.984   0.984   1.008   0.995
   0.993   0.923   0.978   1.062   1.058   0.973   0.945
   0.953   0.980   0.883   0.962   0.994   0.870   0.995
   0.989   1.066   0.965   0.723   1.049   1.156   1.065
   0.990   1.063   0.998   1.051   0.599   1.232   1.059
   1.015   0.981   0.876   1.162   1.236   0.841   1.123
   1.002   0.954   1.005   1.075   1.067   1.128   1.074
```

4. RESULTS

The quality of the results obtained by the methods outlined in this paper will be the subject of a paper submitted to the International Topical Meeting on Mathematics, Computations, and Reactor Physics, Pittsburg, April 1991 with the following title: "CORE FOLLOW STUDIES OF QUAD CITIES CYCLES 1 AND 2 WITH SPECIAL EMPHASIS ON PIN POWER COMPARISONS AT THE END OF CYCLE 2" by C.F. Højerup and E. Nonbøl.

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BWR TYPE REACTORS; C CODES; COMPUTERIZED SIMULATION; FUEL PINS; NEUTRON FLUX; NODAL EXPANSION METHOD; POWER DISTRIBUTION; REACTOR CORES

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